

Towards real-time S-parameter qualification and macromodeling

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Towards real-time S-parameter qualification and macromodeling

Stefano Grivet Talocia

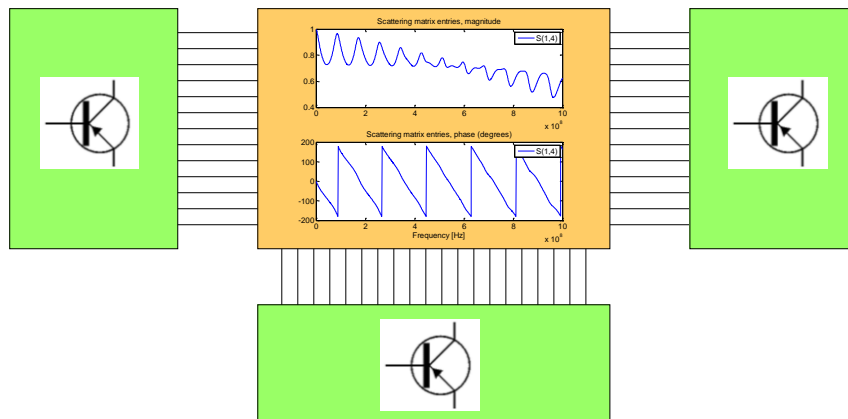
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16th IEEE Workshop on Signal and Power Integrity
IBIS Summit, 16 May 2012, Sorrento, Italy

The objective

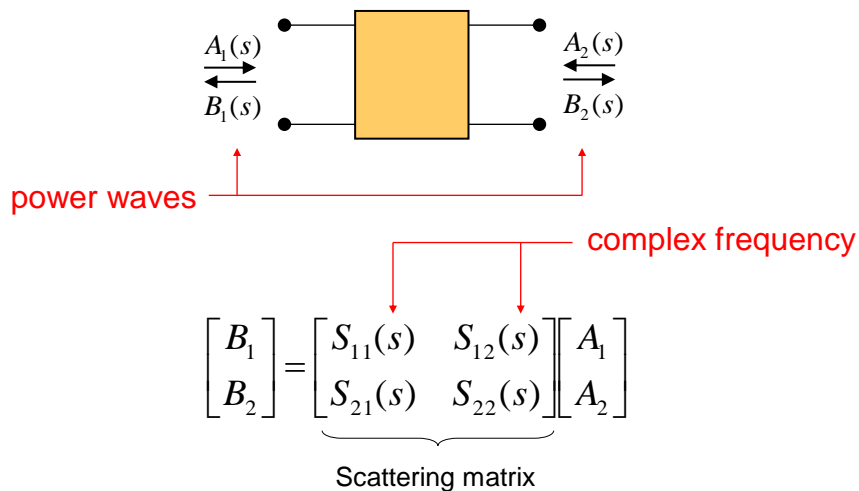
S-parameter block



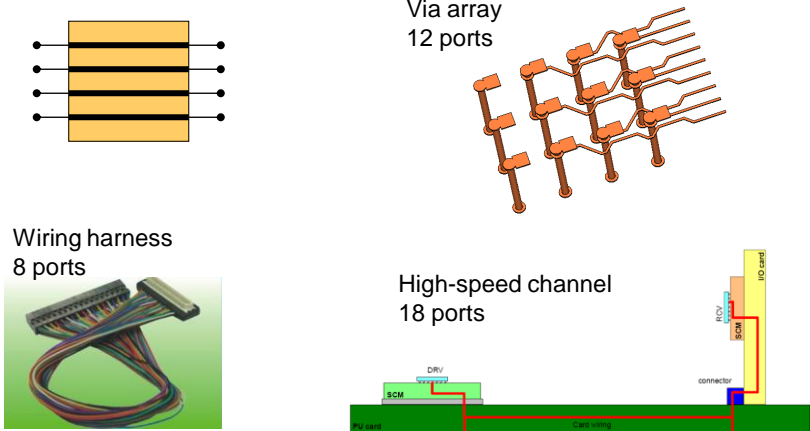
Why S-parameters

- S-parameters are always defined
 - Impedance or admittance may not
- S-parameters are normalized
 - Good numerical properties in simulation
- S-parameters are easily measured
 - Even at very high frequency, good reliability
- Standard format for S-parameters
 - Touchstone files from measurement hardware
 - All field solvers provide S-parameters on output
- Tabulated frequency data
 - Intrinsic IP protection for vendors
 - Do not disclose design details, but only I/O electrical properties
- Best way to represent broadband EM/circuit interactions
 - The essence of Signal and Power Integrity

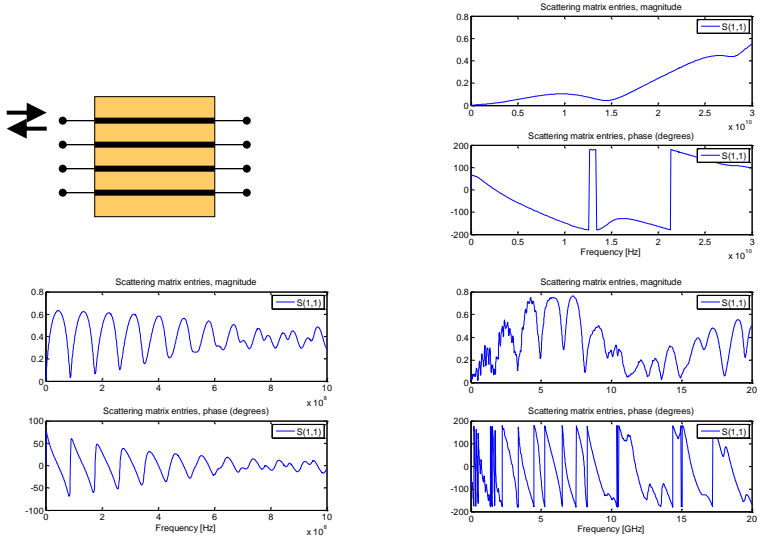
Scattering network functions



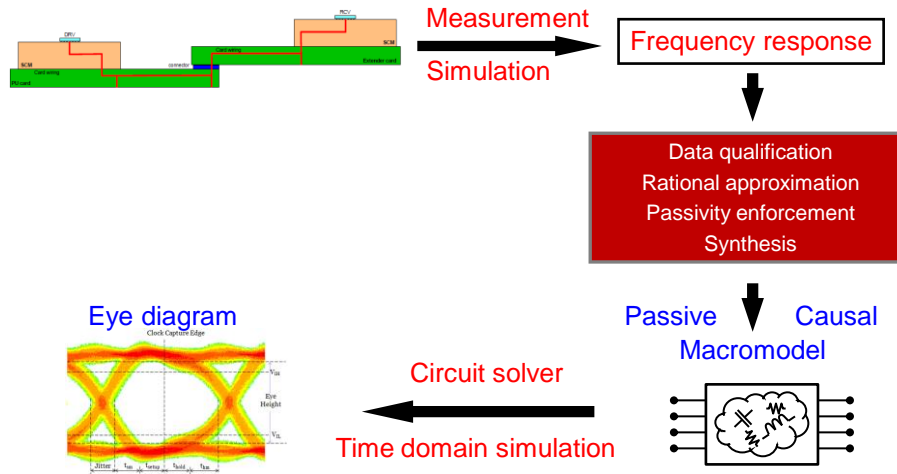
Examples of S-parameter data



Examples of S-parameter data



S-parameter modeling flow

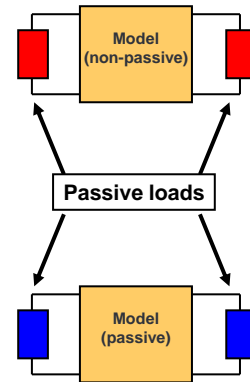
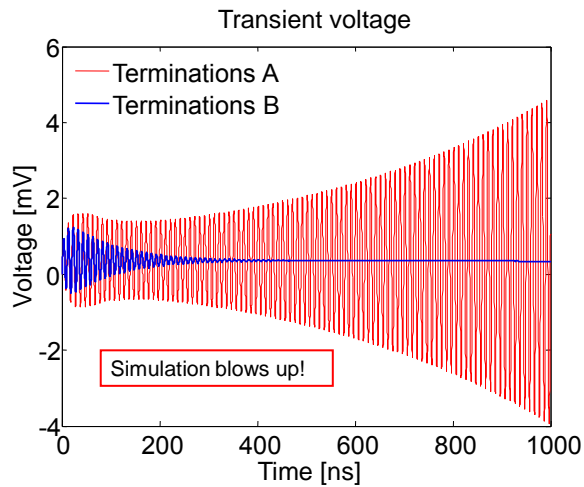


Part I: qualification

A quick overview



Passivity: why?



Passivity

$$\mathbf{S}(-j\omega) = \mathbf{S}^*(j\omega)$$

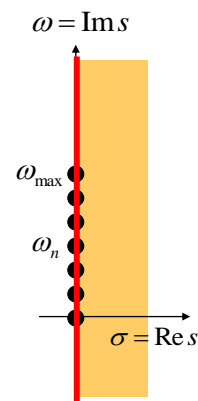
Guarantees real-valued impulse response.
Always assumed by construction

$$\|\mathbf{S}(j\omega)\| \leq 1 \quad \text{or} \quad \max_i \sigma_i\{\mathbf{S}(j\omega)\} \leq 1$$

Energy condition: structure must not amplify signals.
Sometimes called simply "passivity" condition

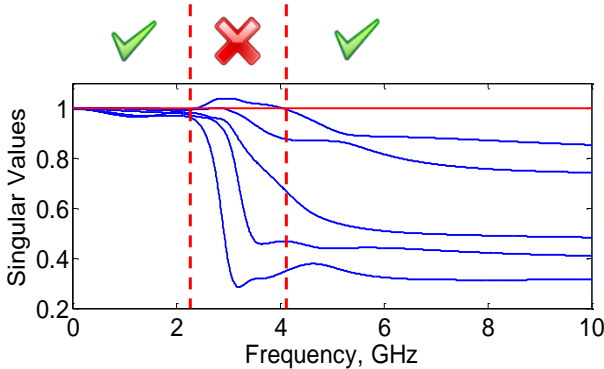
$\mathbf{S}(j\omega)$ is causal

No anticipatory behavior in time-domain.
Note: causality is a prerequisite for passivity!

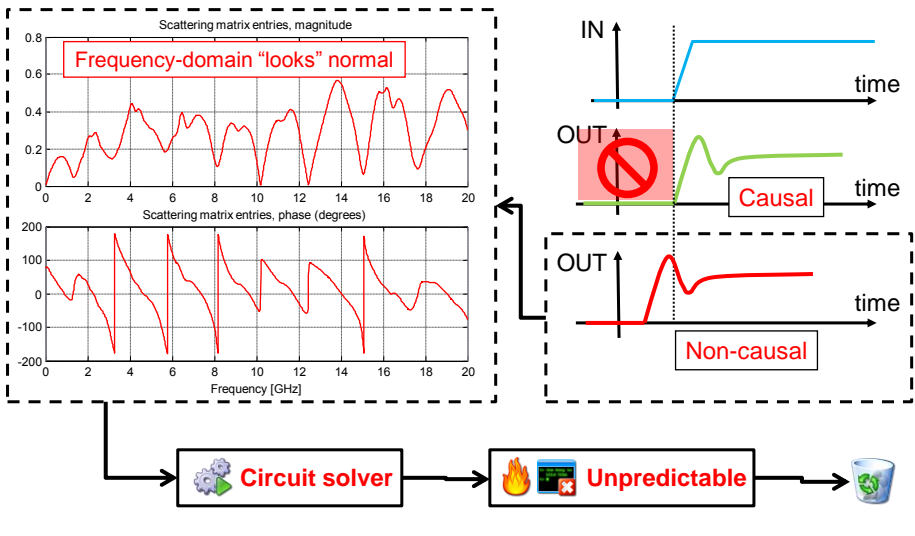


Passivity

$S(s)$ is passive $\Rightarrow \{ \text{singular values of } S(j\omega) \} \leq 1, \forall \omega$

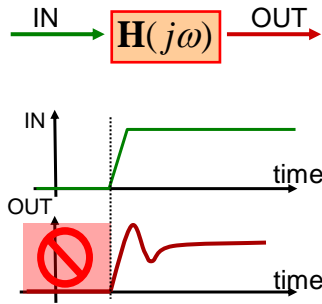


Causality



Causality: definitions

Time-domain



Note: no delay extraction here

Frequency-domain

Hilbert transform

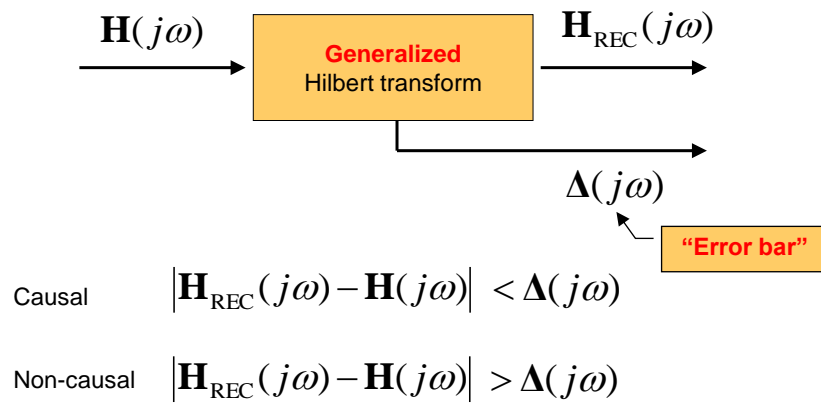
Kramers-Krönig dispersion relations

$$H(j\omega) = \frac{1}{j\pi} \text{p.v.} \int_{-\infty}^{+\infty} H(j\omega') \frac{d\omega'}{\omega - \omega'}$$

Self-consistency

All samples are strongly related

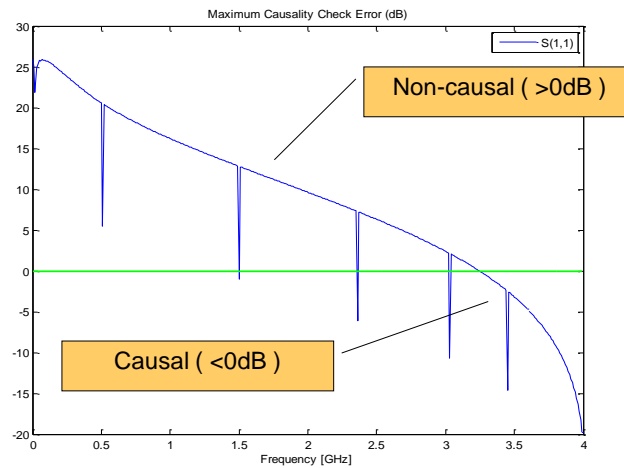
Causality check



Causality check error

$$E_{dB}(j\omega) = 20 \log_{10} \frac{|H_{\text{REC}}(j\omega) - H(j\omega)|}{\Delta(j\omega)}$$

Computed (parallel) for each scattering response



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Part II: macromodeling

An update on recent developments



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Rational function fitting: why?



Circuit solvers understand circuits

Any lumped circuit has rational frequency responses (poles-residues, poles-zeros, ratio of polynomials)

$$S(s) \approx \sum_{n=1}^N \frac{\mathbf{R}_n}{s - p_n} + S_{\infty}$$

Impedance, admittance, scattering

Rational function fitting: why?



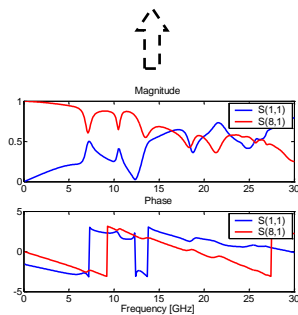
Circuit solvers understand circuits

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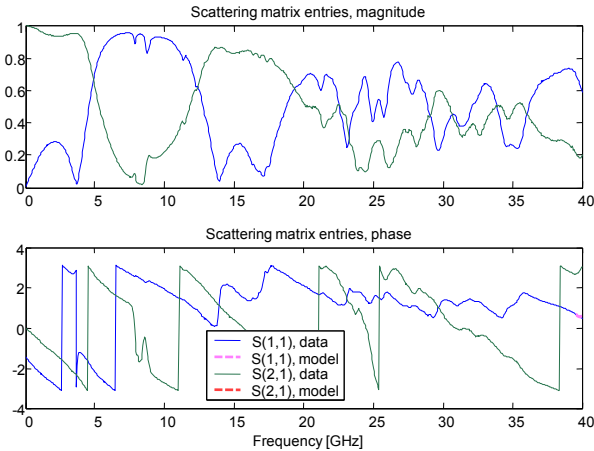
Impedance, admittance, scattering

Extraction of an equivalent circuit is an inverse problem (two-step)



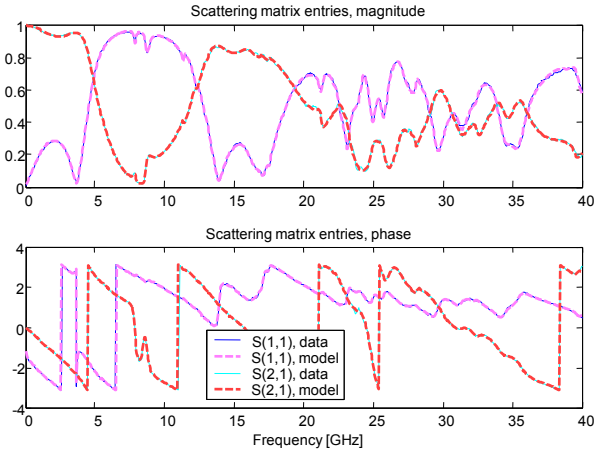
Stripline + launches

Data: measured S-parameters

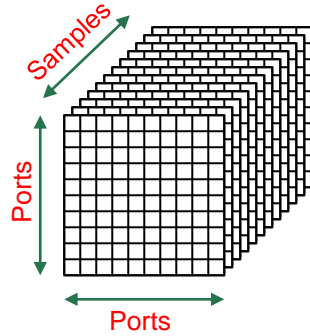


Stripline + launches

Macromodel: 60 poles



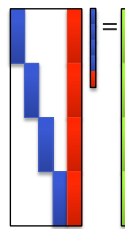
Handling many ports



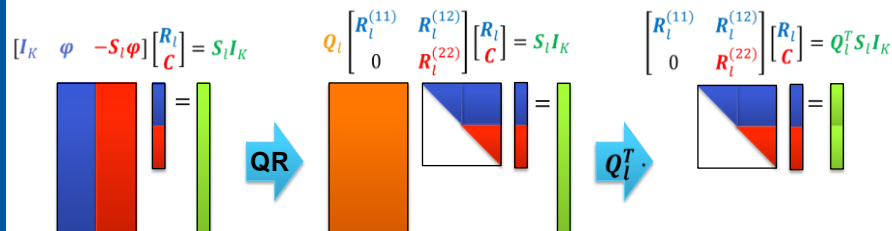
$$\hat{S}_{i,j}(s) \approx \sum_{n=1}^N \frac{R_n^{i,j}}{s - p_n} + S_\infty^{i,j}$$

Processing **all** responses may lead to a **large** system!

Parallel Vector Fitting

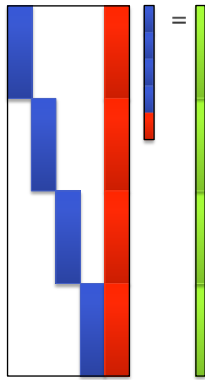


$$\begin{bmatrix} I_K & \varphi & 0 & 0 & \dots & 0 & 0 & -S_1\varphi \\ 0 & 0 & I_K & \varphi & \dots & 0 & 0 & -S_2\varphi \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & \dots & I_K & \varphi & -S_{p^2}\varphi \end{bmatrix} \begin{bmatrix} R_1 \\ R_2 \\ \vdots \\ R_{p^2} \\ \mathbf{C} \end{bmatrix} = \begin{bmatrix} S_1 I_K \\ S_2 I_K \\ \vdots \\ S_{p^2} I_K \end{bmatrix}$$



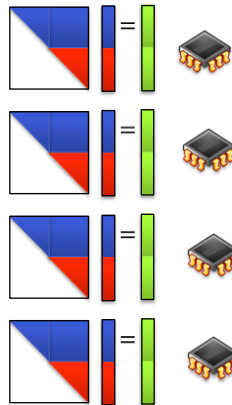
Parallel Vector Fitting

Original LSP



1 GB

QR decompositions



New LSP



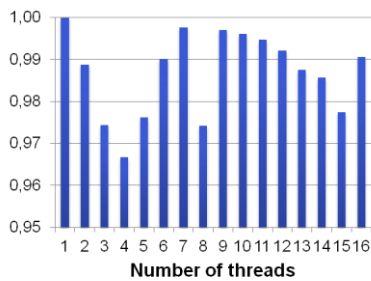
12 MB

$P = 83$ $K = 1228$ $N = 30$

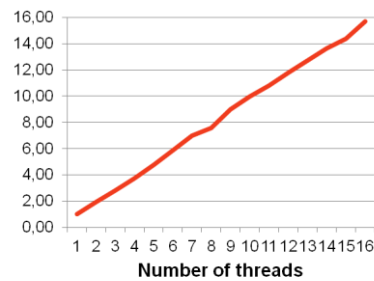
Parallel Vector Fitting

$P = 83$ $K = 1228$ $N = 30$

Parallel efficiency



Speed up

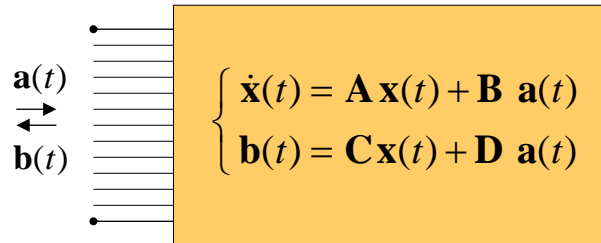


15.7 x



From 193.33 to 12.23 seconds

State-space macromodel realization



$$\mathbf{S}(s) \approx \sum_{n=1}^N \frac{\mathbf{R}_n}{s - p_n} + \mathbf{S}_{\infty} = \mathbf{D} + \mathbf{C}(s\mathbf{I} - \mathbf{A})^{-1}\mathbf{B}$$

Checking macromodel passivity

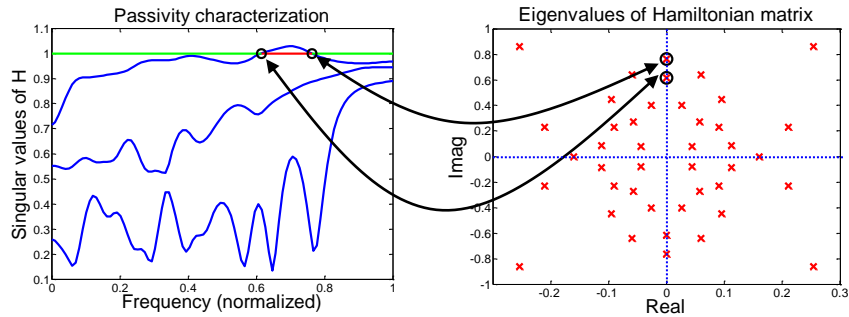
$$\{\text{singular values of } \mathbf{S}(j\omega)\} \leq \mathbf{1}, \quad \forall \omega$$

Eigenvalues of Hamiltonian matrix

$$\mathbf{M} = \begin{pmatrix} \mathbf{A} - \mathbf{B}(\mathbf{D}^T \mathbf{D} - \mathbf{I})^{-1} \mathbf{D}^T \mathbf{C} & -\mathbf{B}(\mathbf{D}^T \mathbf{D} - \mathbf{I})^{-1} \mathbf{B}^T \\ \mathbf{C}^T (\mathbf{D} \mathbf{D}^T - \mathbf{I})^{-1} \mathbf{C} & -\mathbf{A}^T + \mathbf{C}^T \mathbf{D} (\mathbf{D}^T \mathbf{D} - \mathbf{I})^{-1} \mathbf{B}^T \end{pmatrix}$$

Real matrix \mathbf{M} must have no imaginary eigenvalues

Checking macromodel passivity



Theorem

$j\omega_0$ is an eigenvalue of $\mathbf{M} \Leftrightarrow \sigma = 1$ is a singular value of $\mathbf{S}(j\omega_0)$

Passivity enforcement

- Generate a **new passive macromodel**
- Apply **small correction** to **preserve accuracy** through
 - iterative passivity check
 - solution of small-size optimization problems

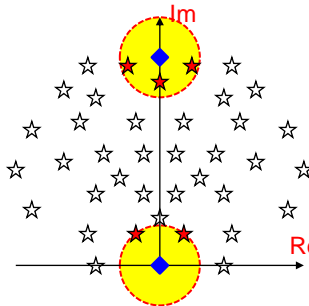
$$\begin{cases} \dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{a} \\ \mathbf{b} = \mathbf{C}\mathbf{x} + \mathbf{D}\mathbf{a} \end{cases} \quad \longrightarrow \quad \begin{cases} \dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{a} \\ \mathbf{b} = (\mathbf{C} + \Delta\mathbf{C})\mathbf{x} + \mathbf{D}\mathbf{a} \end{cases}$$

$$\Delta\mathbf{S} = \Delta\mathbf{C}(\mathbf{s}\mathbf{I} - \mathbf{A})^{-1}\mathbf{B}$$

Passivity check: computing few eigenvalues

We need only all purely imaginary eigenvalues of \mathbf{M}
Iterative single-shift Arnoldi iterations to find few
eigenvalues "close" to imaginary "shift points".

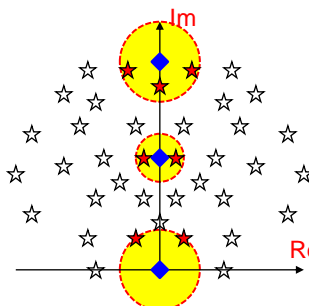
Pick initial
shifts at ends
of spectrum



Passivity check: computing few eigenvalues

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Pick initial
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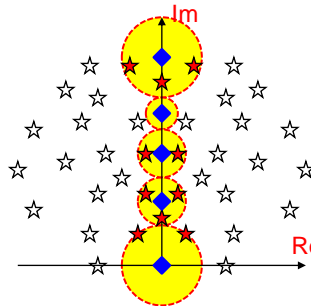


Bisection on
imaginary axis

Passivity check: computing few eigenvalues

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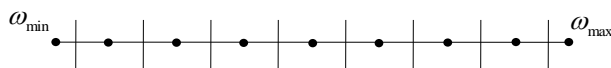
Pick initial
 shifts at ends
 of spectrum



Bisection on
 imaginary axis

The union of all
 disks must have
 no "gaps"!

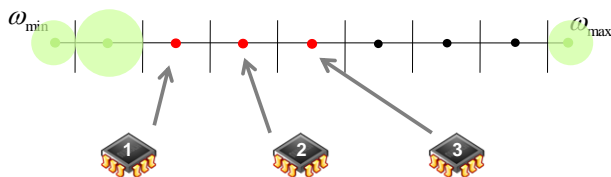
Basic idea: single-shift \leftrightarrow single-thread



Split bandwidth into
 N subbands
 $N = F(T)$
 T= threads

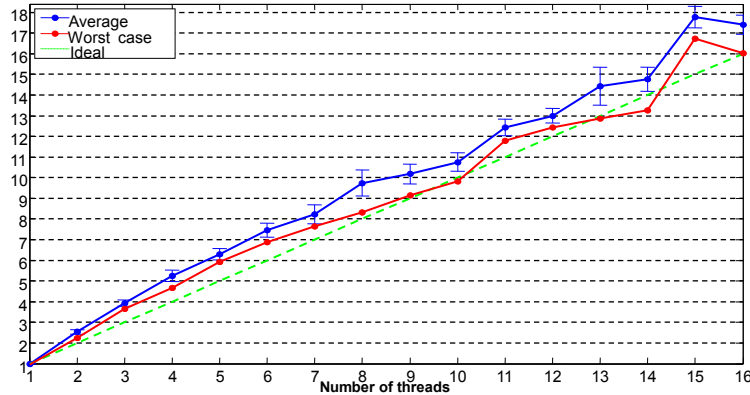


Startup phase



● Ready
 ● In execution
 ● Completed

Speedup (high-speed connector model)



Order	2240	Number of threads	1	2	8	16
Ports	56	Number of λ	90	110	86	84
f_{min}	0 GHz	Analysis time [s]	33.778	13.259	3.369	1.830
f_{max}	21 GHz	Refine time[s]	0.096	0.039	0.021	0.019
α	5	Total time [s]	33.972	13.398	3.487	1.950
N λ_{imag}	22	Speedup		2.5 X	9.7 X	17.4 X

S-parameter modeling flow: a summary



Input

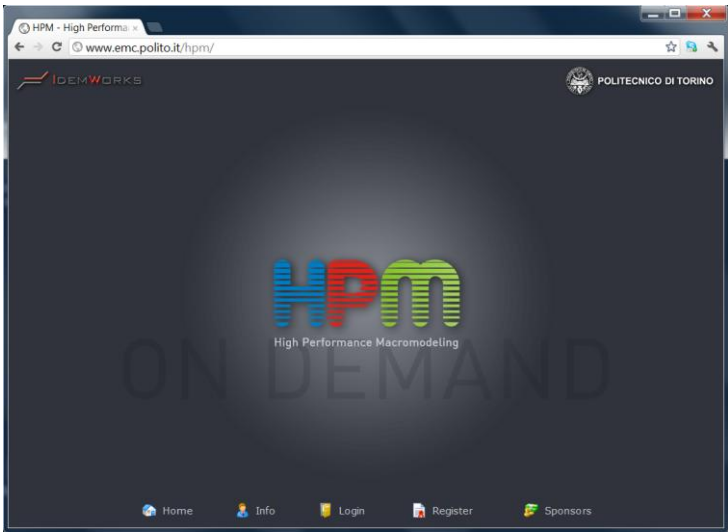
- Tabulated frequency responses ("numbers", "S-parameters")
 - From EM simulations (in-house or external tools)
 - From measurements
 - From vendors (connectors, filters, etc...)
- Standardized (Touchstone format)
- Small-size, compact files
- Hides IP (behavioral data)



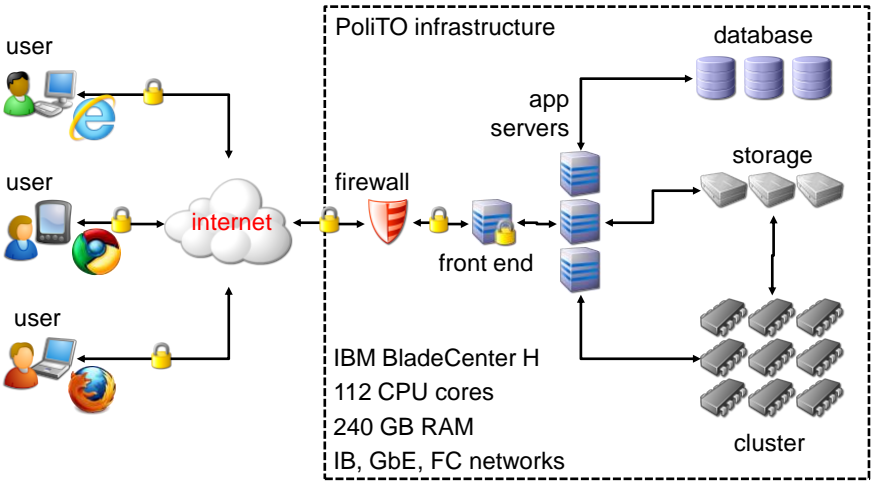
Output

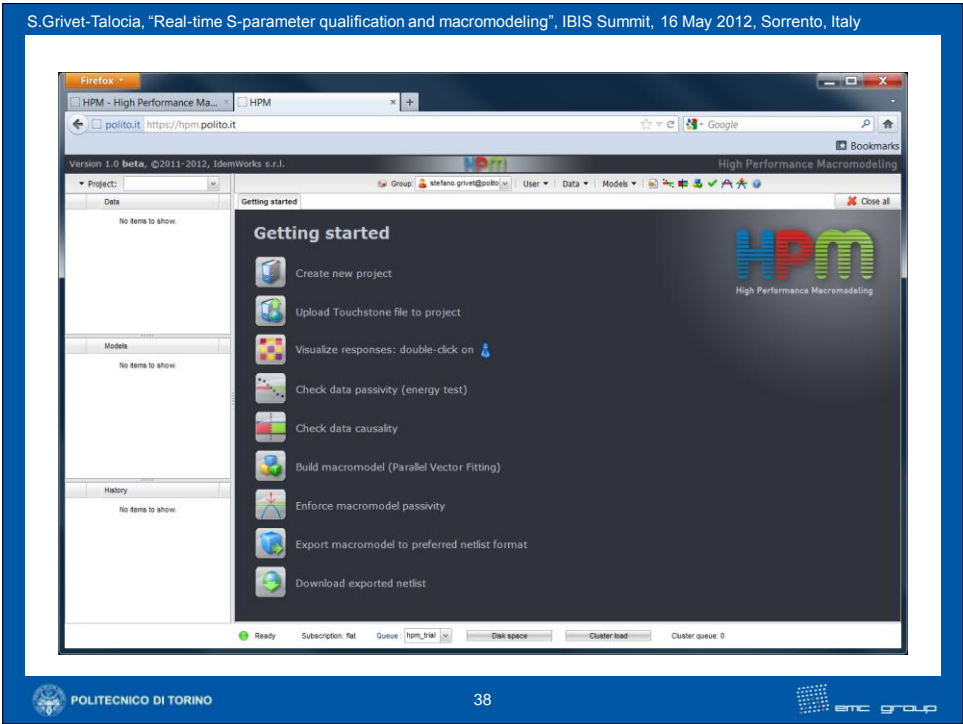
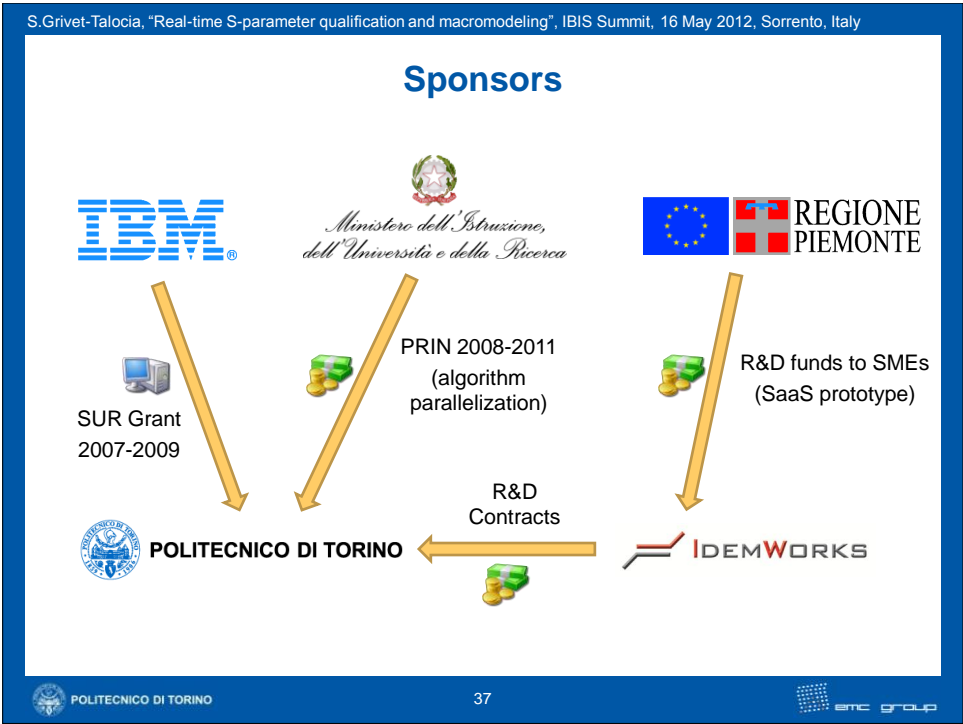
- System-level simulation model ("equation", "netlist")
- Qualification certificate (WHY?)
 - Physical self-consistency (stability, causality, passivity)
 - Guaranteed performance in system-level analysis

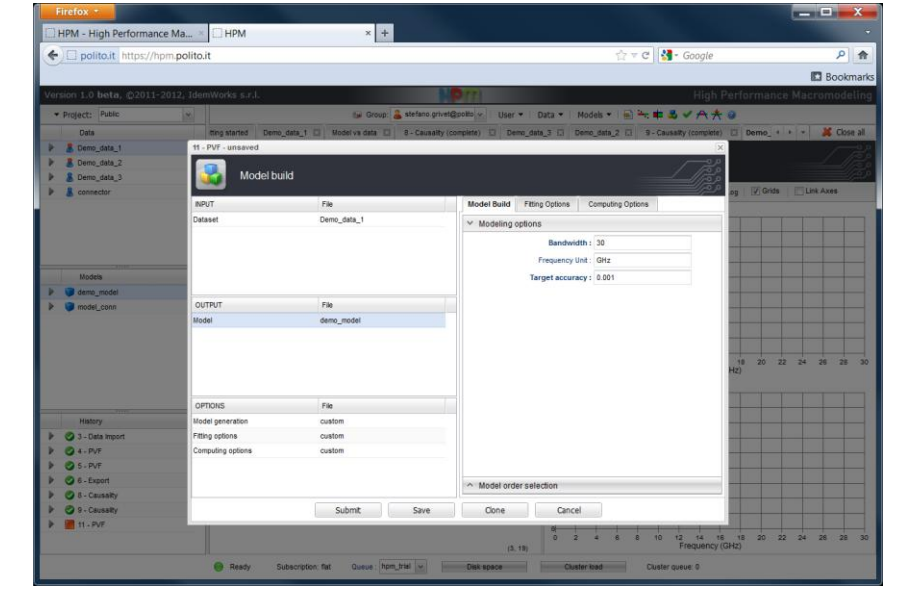
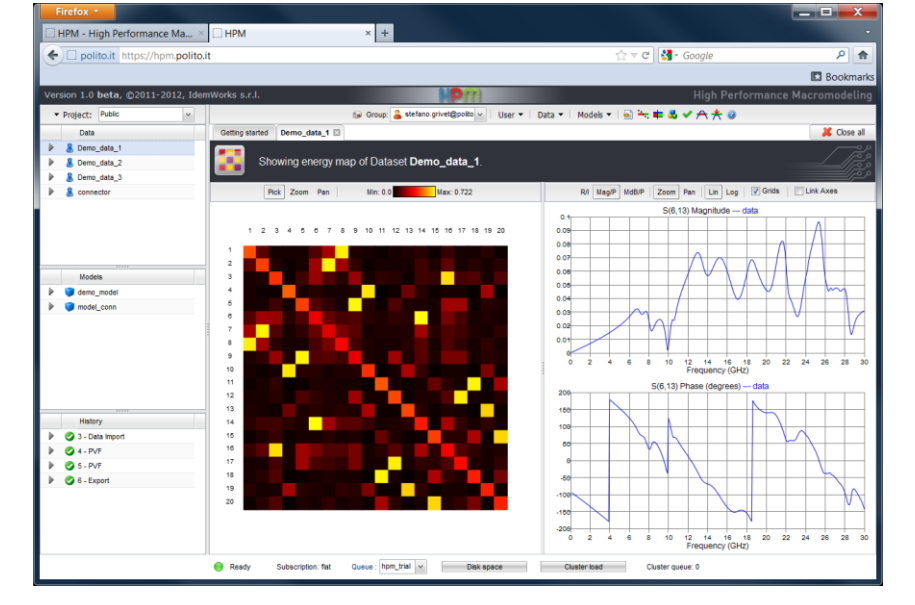
The HPM Service



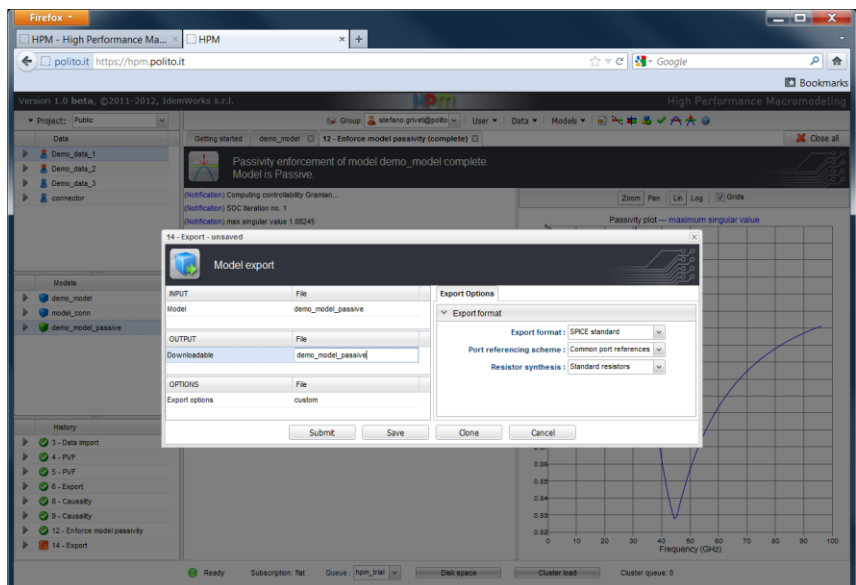
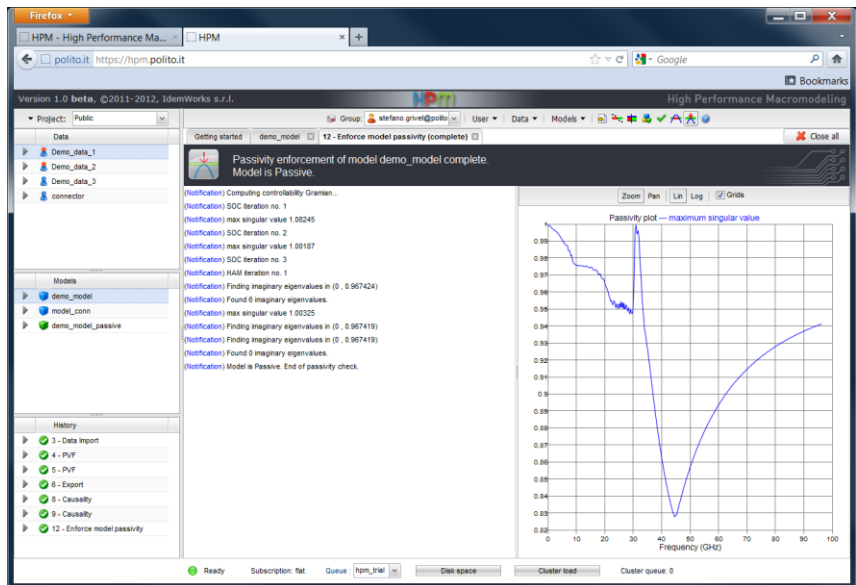
The HPM Service

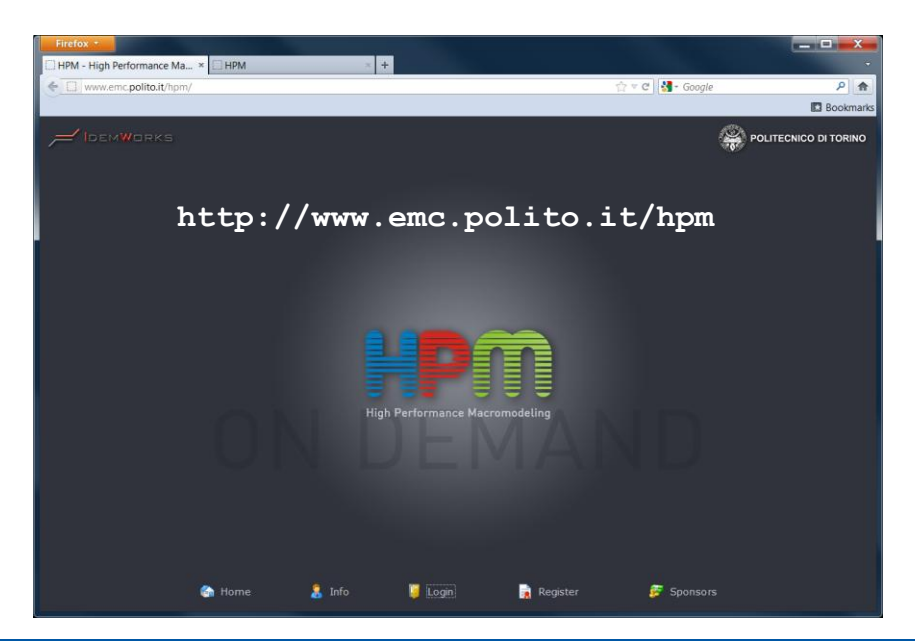
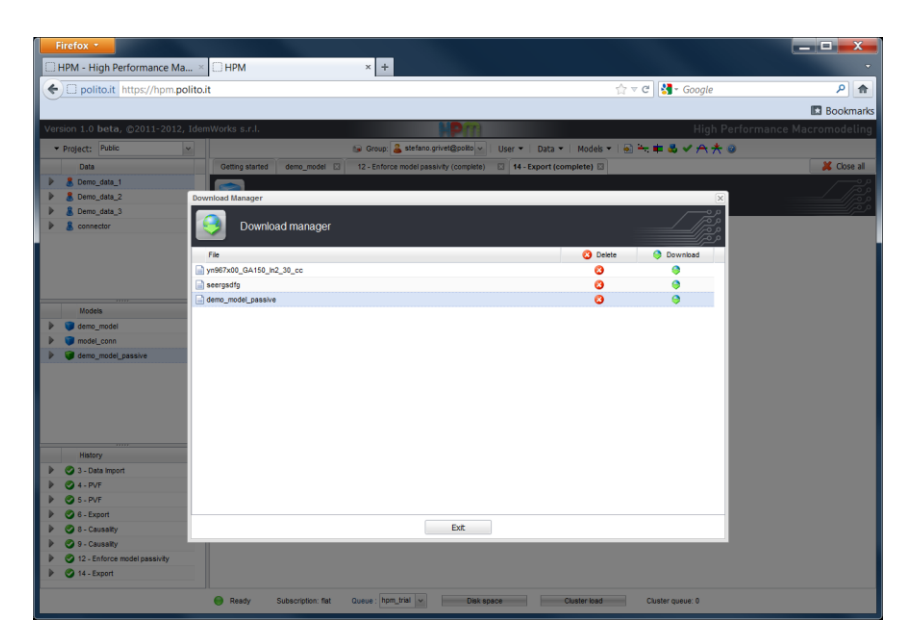












Thank you



<http://www.emc.polito.it>



<http://www.idemworks.com>

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